MONOLITHIC MEMS FILTER BANKS ON RFSOI FRONT-END MODULE

Humberto Campanella[1-2], You Qian[1], Christian O. Romero[1], Joan Giner[1], and Rakesh Kumar[1]*
[1]GLOBALFOUNDRIES Singapore
[2]Tyndall National Institute, Cork, Ireland
* With GlobalFoundries at the time this work was done

ABSTRACT

This work is the first demonstration of a monolithic multiband RF front-end module (RF-FEM), integrating MEMS Lamb-wave filters and switches on 200mm RF silicon-on-insulator (RFSOI) foundry technology. Multiple MEMS filters with photolithography-defined frequencies coexist with RF components in the same wafer. This technology enables vertical integration of RF-FEM components for more compact System-on-Chip (SoC) architectures. The resulting RF-FEMs will then integrate in the same process multi-frequency filter banks, low noise amplifiers (LNAs), and switches, with a footprint reduction up to 50% compared to system-in-package (SiP) modules. The SoC architecture also simplifies the design of interconnection lines and impedance matching networks.

KEYWORDS

MEMS filters, RF front-end modules, Lamb wave filters, monolithic 3D integration, 5G, System-on-Chip.

INTRODUCTION

Vertical integration of MEMS filters and RF integrated circuits (RFICs) is paramount to reduce the RF-FEM footprint. Currently, RF-FEMs integrate 30+ MEMS filter chips using horizontal hybridization SiP architecture, and while they will multiply by 10 times in the next years for 5G cellphones –it is imperative that they keep their current size due to market and ergonomic restrictions. Therefore, there is a need of denser modules with smaller footprint. Previous works demonstrated the feasibility of monolithic integration of bulk acoustic wave (BAW) filters and RFICs on 100mm SiGe process for front-end applications [1-2], monolithic GHz oscillators on GaN process [3], and wafer bonding and film transfer SoC architectures [4-5]. This work reports, for the first time, on the integration of multiple filters with 200mm RFSOI wafer technology manufactured in mass-production environment. This development thus enables multiband MEMS filters, smaller footprint RF-FEMs, and simpler and cheaper process, as it eliminates wafer bonding/transfer costs.

MANUFACTURING METHOD

The monolithic RF-FEM is built on GLOBALFOUNDRIES' 7SWTSOI process, a 200mm RFSOI CMOS platform suitable for switches and LNAs. In this work, variety of single-pole-single-throw (SPST) series and shunt switches and MEMS filter designs connect to build proof-of-concept RF-FEMs. MEMS devices are stacked above the last CMOS back-end-of-line (BEOL) metal. To do so, post-CMOS processing include, at least, dielectric insulators for RF decoupling, sacrificial materials for surface-micromachined cavities of the MEMS device, the MEMS filter layers, and interconnect vias metallization for MEMS-switch contacts (see Fig. 1).

The thermal budget of the MEMS manufacturing process is kept below 450 °C for CMOS compatibility. The MEMS process starts with RFSOI wafers with RFIC devices (Fig. 2a), and by depositing and chemical mechanical polishing (CMP) planarization of a silicon dioxide layer thick enough to cover the last CMOS metal (Fig. 2b). Silicon (Si) is sputtered and patterned on the oxide, followed by further chemical vapor deposition (CVD) and CMP of oxide to deliver a 1-µm sacrificial layer on flat surface (Fig. 2c). The MEMS filter stack consists of AlN seed layer, bottom Mo electrode, AlN acoustic layer, and top Mo electrode and is formed on the flat Si sacrificial (Fig. 2d). Three different vias provide contacts to interconnect the top and bottom Mo electrodes to the CMOS last metal. Metallization uses aluminum copper (AlCu) lines with robust thickness for RF performance and sidewall coverage for large step (Fig. 2e). Finally, release vias are created and the sacrificial Si layer is etched to create cavities underneath the MEMS filters (Fig. 2f).

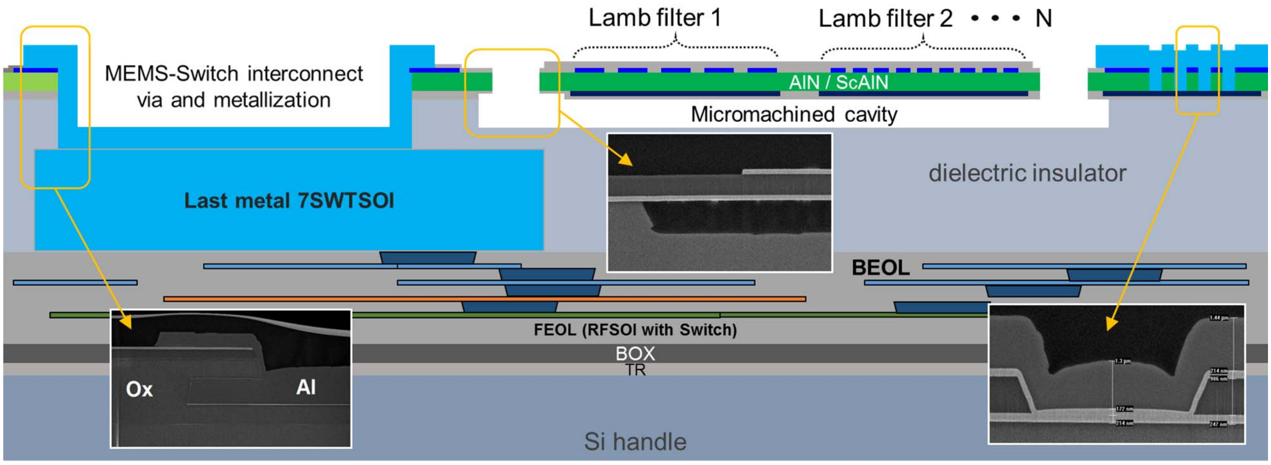

Figure 1: Monolithic RF front-end module architecture: Lamb MEMS filters on GF 7SWTSOI 200mm RFSOI switches.

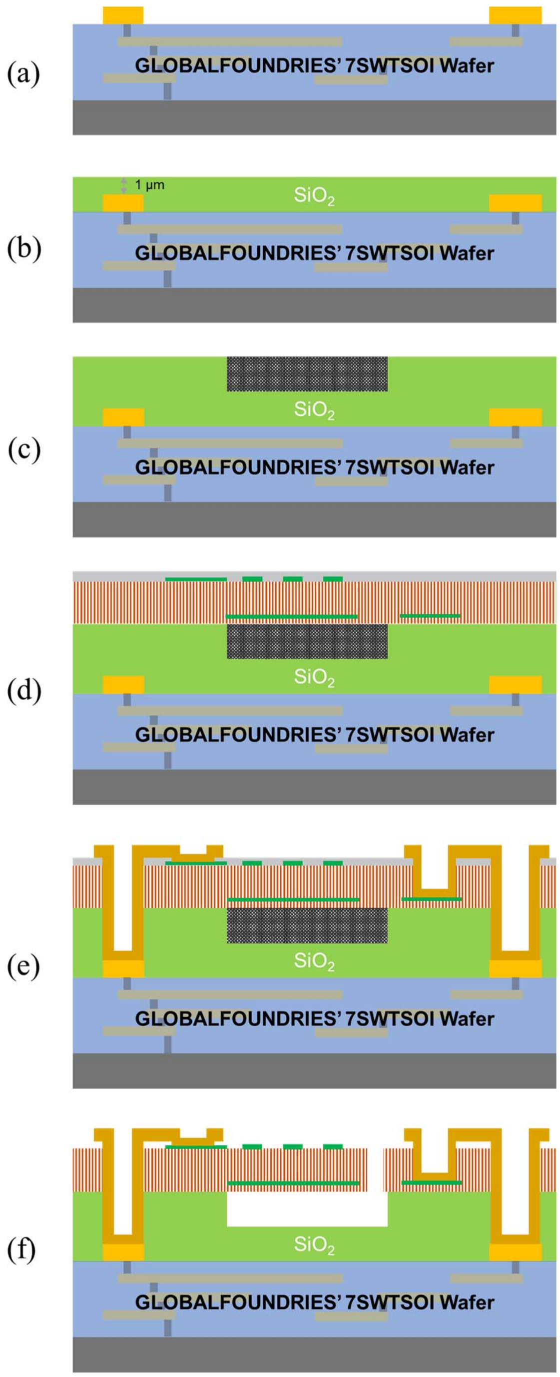

Figure 2: MEMS filter bank manufacturing flow: (a) Start RFSOI wafer; (b) SiO_2 dep and CMP; (c) Si sacrificial layer and oxide dep, patterning and CMP; (d) MEMS piezoelectric stack; (e) Contact vias and metallization; and (f) Release vias, sacrificial etch, and MEMS release.

RF FRONT-END MODULE DESIGN

Fig. 3 shows fabricated RF-FEMs integrating MEMS filters. Fig. 3(a) shows a Lamb-wave MEMS filter using a ladder topology integrated to a SPST RFSOI switch placed on the side of the filter. Fig. 3(b) shows another MEMS device placed above the RFSOI switch (the last CMOS metal lines can be seen in the background). Figure 3(c) is a close-up view of the IDT electrode geometry of a Lamb-wave filter with CD of 400 nm. Such small CD capability enables high frequency filters for 5G sub-6GHz bands.

Fig. 4 shows finite element modeling of the impedances of the acoustic Lamb wave modes of one example MEMS resonator used to build a 1.5GHz filter. The observed resonances include symmetric (S) and asymmetric (A) modes in a wide 3GHz frequency span. Simulation data (red/light) show good agreement to experimental characterization (black/dark), and are used in the synthesis of 1.5GHz Lamb wave filters.

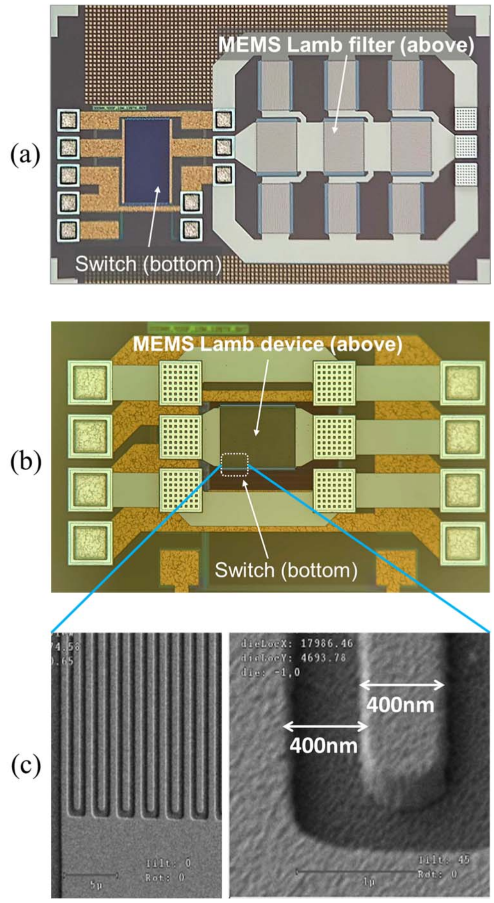

Figure 3: Monolithic RF front-end module devices (examples): (a) MEMS-on-switch layout; (b) Side-by-side MEMS and switch (MEMS is above the switch in the vertical axis); (c) Zoom-in of the IDT electrodes with min. CD of 400nm.

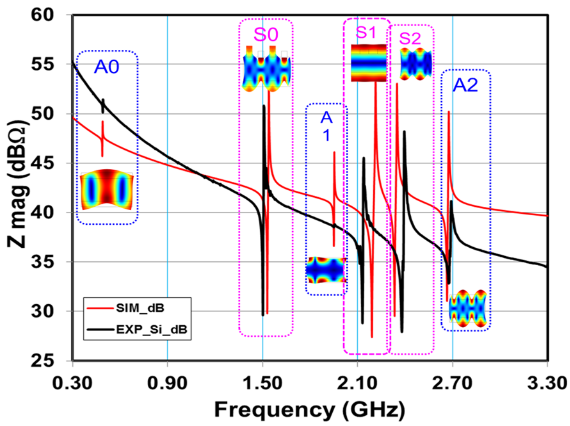

Figure 4: Symmetric and Asymmetric Lamb modes: Experimental (black) vs. finite element simulations (red).

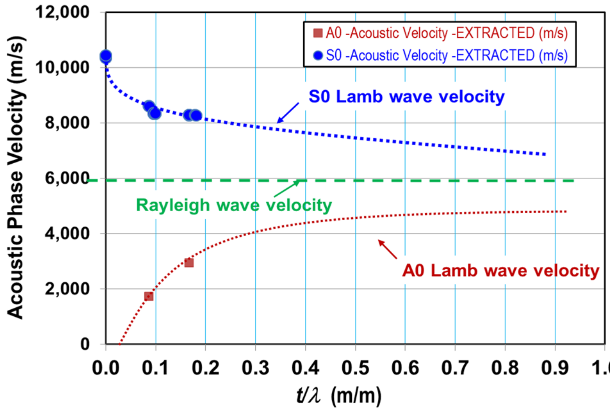

Figure 5: Acoustic phase mode velocities of the piezoelectric AlN layer of the MEMS Lamb filters (extracted from S21).

Figure 5 plots the extracted acoustic mode velocities used in the design of the MEMS filters. The higher phase velocities supported by thin-film Lamb modes –compared to conventional SAW modes, enable the higher frequency requirements of 5G band filters. This chart provides critical information for designing the central frequency of filters, in particular at high frequencies where velocities may converge to the Rayleigh mode velocity.

RF CHARACTERIZATION

RF characterization presented here is evidence of the multi-frequency capability of the monolithic integration of RF front-end module components.

One relevant question out of the monolithic integration development is whether building MEMS filters on RFSOI circuits already existing in the wafers will change the process and electrical parameters of the switches. The plots in Fig. 6 compare the three main parameters considered in this study, before and after the MEMS filter processing on the RFSOI wafers: (a) Ron×Coff product, (b) Isolation, and (c) Insertion Losses. Minimum change in all parameters of the switch demonstrate the monolithic stacking of the filter layers had no negative impact in the performance.

Fig. 7 shows the wideband S21 responses of 850MHz and 1.5GHz switched filter RF-FEMs, for the ON/OFF states of the filter, and the corresponding circuit schematics. Both filters coexist in the same wafer/die with other devices, including BAW filters.

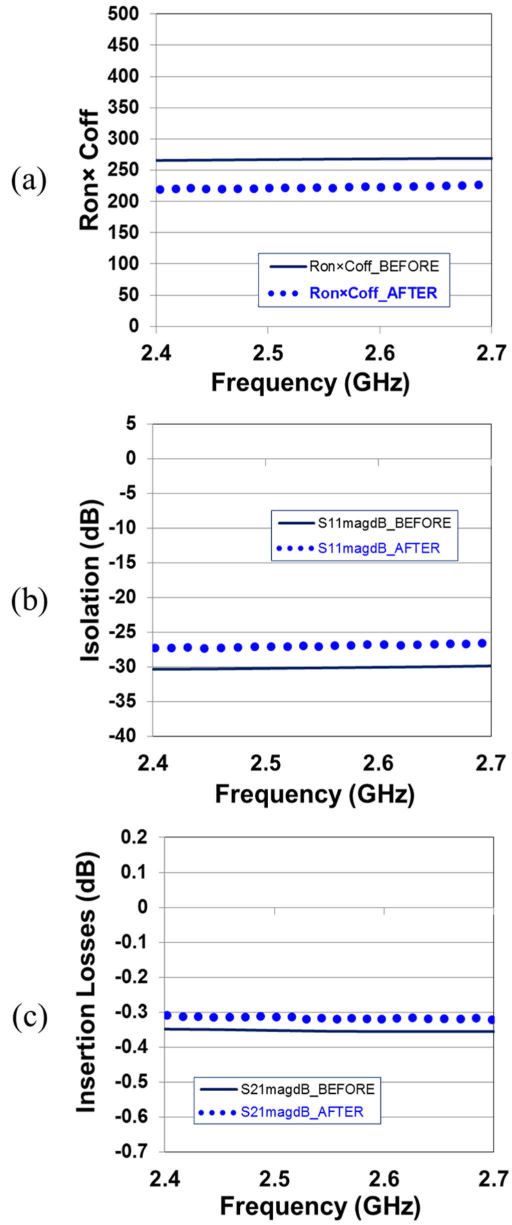

Figure 6: Minimum impact of monolithic integration to the RFSOI switch performance: (a) Ron×Coff product, (b) Isolation, (c) Insertion Losses.

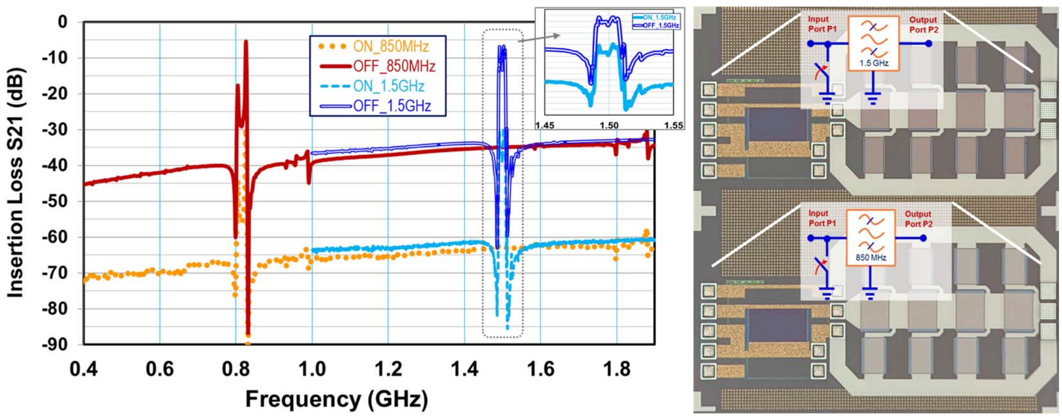

Figure 7: S21 responses of 850MHz and 1.5 GHz filters in the ON and OFF switch states. Right: Micrograph with both filters coexisting in the same die (corresponding circuit schematics in the insets). Shunt switches used in the RF-FEM provide > 25dB isolation between states. (RF signal is shunted in the ON state)

5G RF-FEM INTEGRATION DISCUSSION

Monolithic integration of RF front-end modules pose several challenges, from material development, to device integration, to application development:

First, the piezoelectric material has to enable most use cases for critical 5G bands. The demonstrators presented in this work use AlN as acoustic layer. However, as AlN has been mainstream material for BAW filters for 4G/LTE and WiFi coexistence filters, its piezoelectric properties are insufficient to deliver larger bandwidths required for many 5G bands, if Lamb filters are thought as a candidate technology. On the other hand, a conventional BAW filter process only allows a single filter design per wafer in order to make it economically viable. Integrating multiple filters in the same wafer die would require a photo-lithographically defined filter bank structure, i.e. Lamb filters. Nonetheless, a Lamb filter using AlN is also unfeasible for most 5G bands as lateral modes feature much smaller piezoelectric coupling coefficients, typically one quarter than those of the longitudinal modes used in BAW filter design. Therefore, we propose scandium-doped AlN (ScAlN) as a key enabling material for critical 5G bands. GLOBALFOUNDRIES simulations predict increased coupling coefficient and fractional bandwidths of Lamb filters up to 4.5% with 20% Sc concentration (by atomic weight). These figures will cover most of use cases needed in 5G with multiple bands integrated in the same module die.

Second, the design of a monolithic RF-FEM requires the establishment of a design methodology for mode decoupling and impedance matching. In conventional SiP modules, this issue is addressed at the module integration level, where external matching networks and decouplers are integrated as source mounted devices (SMD) or embedded in the RF laminate tracks. The requirement nowadays is for 5+ filters in the module, bigger modules integrating as much as 16 filters as of 2019. In principle, the SoC architecture provided by our monolithic integration approach would simplify the matching and decoupling networks design, but will put the effort at the silicon level. Acoustic mode coupling and 10+ filter input and output ports impedance matching, along with Si-embedded passives is the big challenge to be addressed.

Last but not the least, the monolithic architecture proposed here provides seamless integration for virtually any application and MEMS and CMOS technology. Technology matching is more related to the application space and the use cases. Fig. 8 shows some suitable applications wherein different MEMS structures find suitable integration with CMOS and RF CMOS technologies, including the obvious cases of standard and high-resistivity Si substrates.

CONCLUSIONS

This work is the first demonstration of a monolithic multiband RF front-end module (RF-FEM). Feasibility of the monolithic approach leverages on the multi-frequency single-chip capability. Further material engineering of the acoustic filter will enable larger bandwidths required for 5G band applications. The monolithic architecture proposed here provides seamless integration for virtually any application. Further developments of this technology will explore integration and application optimization, as well as ScAlN integration for 5G sub-6GHz RF-FEMs.

REFERENCES

[1] M. -A. Dubois, C. Billard, C. Muller, G. Parat and P. Vincent, “Integration of high-Q BAW resonators and filters above IC,” *Dig. Technical Papers IEEE Solid-State Circuits Conference, ISSCC 2005*, San Francisco, CA, 2005, vol. 1, pp. 392-606, Feb. 2005

[2] D. Ruffieux et al., “A Narrowband Multi-Channel 2.4 GHz MEMS-Based Transceiver,” *IEEE J. of Solid-State Circuits*, vol. 44, no. 1, pp. 228-239, Jan. 2009

[3] B. W. Bahr, L. C. Popa, D. Weinstein, “16.8 1GHz GaN-MMIC monolithically integrated MEMS-based oscillators,” *Dig. Technical Papers IEEE Solid-State Circuits Conference, ISSCC 2005*, vol. 1, pp. 304-306, Feb. 2015

[4] K. B. Ostman *et al.*, “Novel VCO Architecture Using Series Above-IC FBAR and Parallel LC Resonance,” *IEEE J. of Solid-State Circuits*, vol. 41, no. 10, pp. 2248-2256, Oct. 2006

[5] A. Kochhar *et al.*, “Monolithic fabrication of film bulk acoustic resonators above integrated circuit by adhesive-bonding-based film transfer,” *Proc. IEEE Ultrasonics Symposium*, pp. 1047-1050, Oct. 2012.

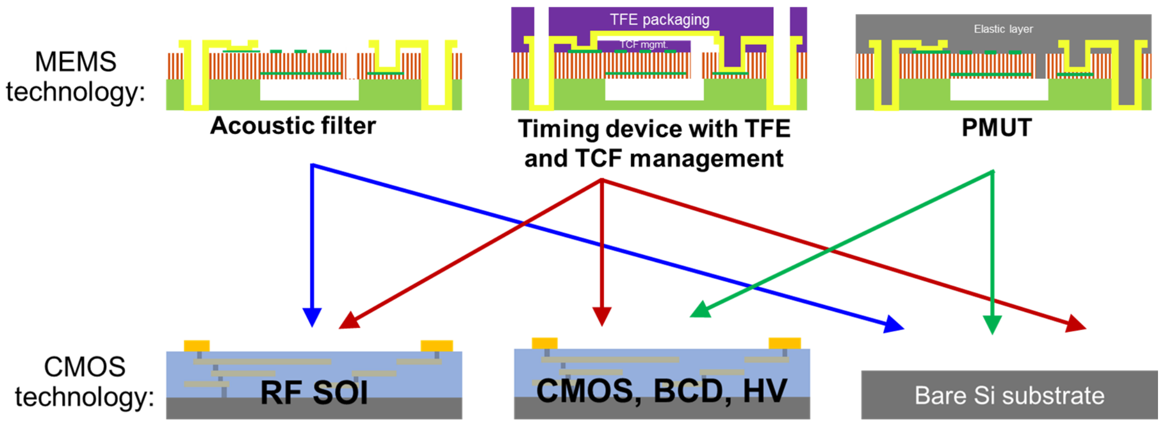

Figure 8: Monolithic integration scenarios for variety of MEMS and CMOS technologies.